DCB, 4ENF and MMB Delamination Characterisation of S2/8552 and IM7/8552

Final Technical Report

by

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13. ABSTRACT (Maximum 200 words)

The aim of this work was to characterise materials S2/8552 and IM7/8552 using methods developed in a previous project (contract N68171-96-C). Delamination onset was measured using servo-hydraulic and multi-station test equipment designed to test DCB, MMB, and 4ENF specimens The electro mechanical multi-station equipment was used to generate delamination onset date to 10^8 cycles at 20 Hz. For both materials, a consistent decrease in the values of G were observed between 10^0 and 10^8 cycles. The static fracture toughness was higher for S2/8552 than for IM7/8552 for Mode I, Mode II and mixed mode loading. A more cost effective method of generating high cycle fatigue data has been developed.

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1.0 SYNOPSIS

This report describes the characterisation of S2/8552 and IM7/8552 under room temperature/dry conditions. Mode I (DCB), Mode II (4ENF) and Mixed Mode Bending (MMB) samples were tested quasi-statically, as well as fatigue delamination onset tests to a maximum of 100 million cycles (10^8). A unique multi station test machine designed and developed at MERL was used to perform the high-cycle delamination onset tests.

2.0 INTRODUCTION

The Vehicle Technology Centre (VTC) within the Army Research Laboratory (ARL), has Co-operative Research and Development Agreements (CRDAs) on composite material rotor systems. The CRDA's are investigating delamination in tapered flex beams that represent a critical section of the hub which are subjected to axial tension and bending loads. The Principal Investigator is Dr. Kevin O'Brien of ARL/VTC at NASA Langley Research Center. The methodology for predicting durability and damage tolerance in these programmes is based on fracture mechanics. The structure is analysed to determine the values of strain energy release rate *(G)* at critical locations in the structure with different delamination lengths. These values of *G* are compared with generic materials fracture data to predict if a delamination will initiate and grow.

To experimentally determine if the composite rotor hubs will delaminate in fatigue, a single flex beam has been tested at VTC for close to 10,000,000 (10^7) cycles. However, because of stroke and frequency limitations on typical hydraulic load frames, it is not feasible to fatigue test the flex beam laminate beyond 10^7 cycles even though rotor hubs may easily experience between 10^8 and 10^9 cycles in service. Furthermore, should the design change, the fatigue tests would have to be repeated. Hence, it is proposed to use analysis and long term materials fracture data as a design evaluation tool to predict delamination onset in structures such as the flex beam after long term fatigue.

Fracture in these structures may be from tension or peel forces, mode I, from shear forces, mode II or from a combination of peel and shear forces, mixed mode I/II. The specimens to characterise these delamination modes are the double cantilever beam (DCB) specimen, the end-notched flexure (ENF) specimen, and the mixed mode bending (MMB) specimen. To provide a comparison for many different structural applications, the material's delamination onset criteria must be generated both under quasi-static conditions and in fatigue for up to 10^8 cycles over a range of fracture modes. These criteria are integral to the success of the research conducted under the CRDAs but also have wider application as generic materials delamination fatigue criteria.

This project investigates the long-term fatigue fracture properties of glass and carbon reinforced plastic materials for these rotorcraft applications. Two materials are used, namely S2/8552 and IM7/8552. The data complements data generated in a previous project using the double cantilever beam (DCB) specimen under contract number N68171-96-C-9061.

The objective of this work is to generate these long-term data in a cost-effective manner. To achieve this, use is made of a unique multi-station facility at MERL for testing multiple specimens. Modifications to the machine and software were required to accommodate the 4ENF and MMB specimens. Two test systems are used to generate the delamination onset data in a range of durations from 1000 cycles to 100 million cycles. The multi station machine for high cycle tests and an MTS servo-hydraulic system for shorter duration tests.

3.0 SPECIMENS AND TEST PROCEDURES

3.1 Mode I DCB Tests

The samples for the quasi-static and fatigue DCB tests were fabricated in S2/8552 and IM7/8552, with a nominal width of 20mm. The initial delamination length (a_0) was nominally 50mm. The specimens were manufactured at BHTI, cut at NASA Langley and distributed to MERL.

The quasi-static tests were all conducted on a screw driven Lloyd test machine to ASTM D5528. All tests were conducted with delamination from the insert. Three tests were conducted for each material at room temperature. The thickness and width of each test specimen were measured at three points along the length and the average value determined and used for the calculation of mode I interlaminar fracture toughness, G_{Ic}. The edge of each test specimen was coated with a water-based typewriter correction fluid and a grid marked on the side of the specimen. Lines were marked at 1mm intervals for the first 10mm and subsequently at 5mm intervals to a delamination length of at least 90mm.

For all specimens, the hinge (see Figure 3.1) was clamped firmly in the test grips with the specimen aligned. Deflection was applied at a rate of 0.5mm/min. As the load increased the delamination length, a, was measured on one side of the test specimen using a microscope at

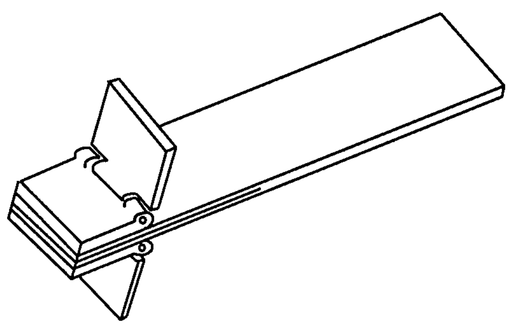


Figure 3.1 Double Cantilever Beam Specimen (DCB)

approximately X25 magnification. At certain intervals of delamination length, the load and the deflection were noted. Throughout the test, the load/deflection trace was stored on the computer. The results of all the static tests were calculated using the different methods given in ASTM D5528.

The DCB fatigue tests were performed using ASTM D6115. The fatigue delamination onset tests were performed on one of 2 types of test machine. The shorter duration tests were performed on a servo-hydraulic MTS test system with a special fixture that allows up to four DCB test specimens to be cycled together with load monitoring on each station (see Figure 3.2). This fixture allows accurate alignment of the test specimen with the load path. Each station is monitored using a piezo-resistive load cell giving accurate measurements of the load applied to each specimen. The test fixtures are shown in Figure 3.3

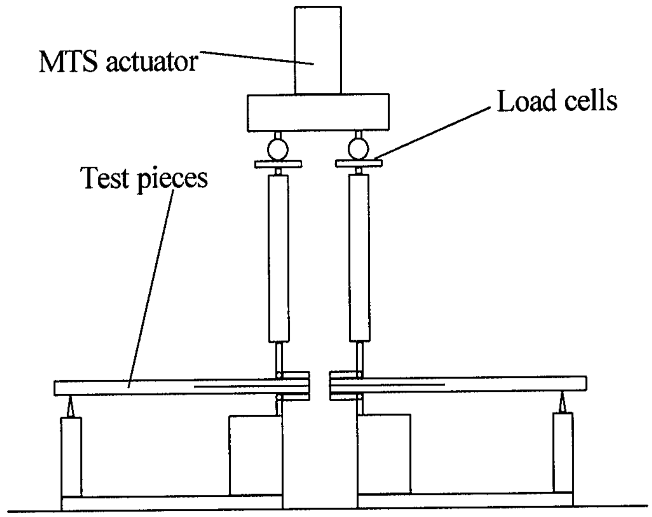


Figure 3.2 Schematic of DCB test rig for fatigue tests

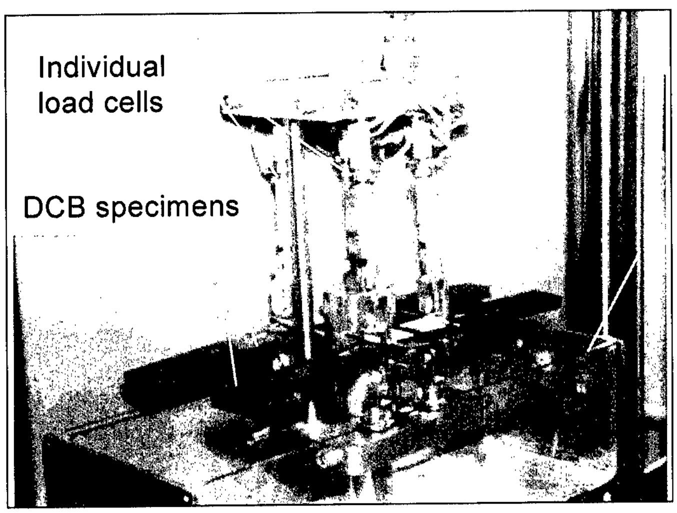


Figure 3.3 DCB Fatigue Fixture for servohydraulic test machine

The longer duration fatigue tests were performed on a multi-station test machine (Figure 3.4) designed at MERL for the testing of fracture mechanics samples to high cycles, where the use of servo-hydraulic equipment is prohibitively expensive. These tests were run at 20Hz to a maximum run out of 100 million cycles as specified by ERO. This test equipment allows up to six test specimens to be cycled together with load monitoring on each station.

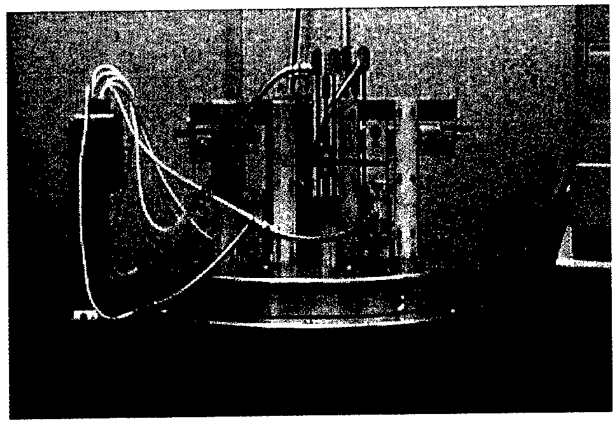


Figure 3.4 Multi-station test machine for high cycle testing

In both test machines, the outputs from each load cell are monitored through specialist software developed at MERL that monitors each channel and records the test specimen compliance throughout the test duration. These data are saved at specified cycle intervals and can be accessed through a spreadsheet once the test is completed. A plot of compliance vs. cycles is displayed in real time on the screen as well as the measured values so that the test can be stopped at the appropriate level of delamination growth or compliance change.

The DCB specimens were cycled between a minimum and maximum displacement, d_{min} and d_{max} , of 0.1 at a frequency of 5Hz or 10Hz for the tests on the servo-hydraulic test machine and at 20Hz for the tests on the unique multi-station test machine.

For the DCB specimens, delamination onset tests were terminated after the compliance had increased by at least 5% or the test duration had reached 100 million cycles. The data were reduced using Equation 3.1.

$$G_{\mathrm{I}max} \quad \frac{3P_{max}\delta_{max}}{2b(a \quad \mathrm{D})} \qquad (3.1)$$

The value of m used for the fatigue tests was the average generated from the quasi-static test data.

3.2 Mode II 4ENF Tests

The test fixture was a standard four-point bend fixture shown schematically in Figure 3.5. The loading rollers were 6mm diameter. The pinned centre loading roller was achieved by applying the load via a ball bearing. The loading rate for all the quasi-static tests was 0.5mm/min. The displacement of the centre span of the beam was measured directly from the crosshead displacement.

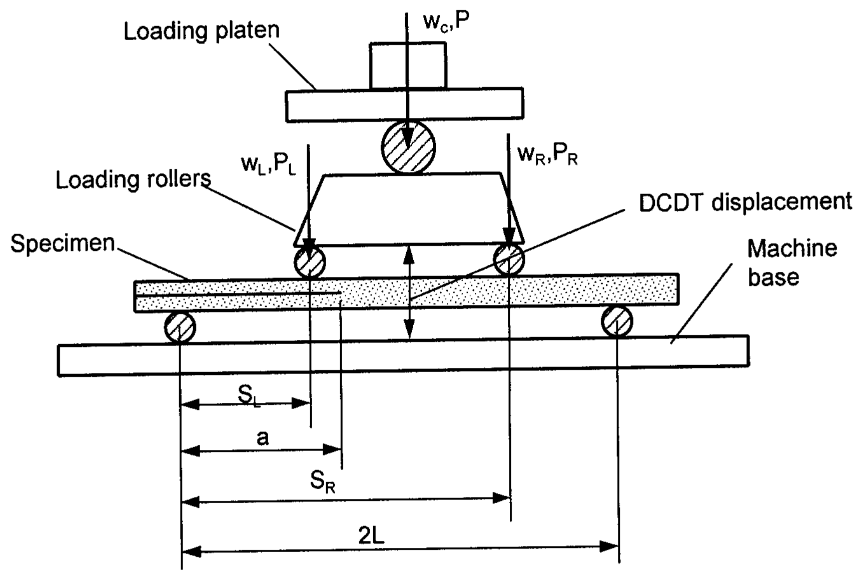


Figure 3.5 Schematic of 4ENF Test

The quasi-static tests were all conducted on a screw driven Lloyd test machine. All tests were conducted with delamination from the insert. Three tests were conducted for each material at room temperature using a span of S_L 20mm and S_R 80mm. The total span length ($2L$) was 100mm in both sets of tests. The thickness and width of each test specimen were measured at three points along the length and the average value determined and used for the calculation of mode II interlaminar fracture toughness, G_{IIc}.

The sides of the specimen were painted with white paint and marks placed every 5mm. The specimens were loaded until the delamination was visibly observed to reach the right hand loading roller. During the test, a deep field microscope was used to monitor the delamination as it grew. This gave data to allow the compliance calibration constants to be calculated. Compliance values determined during the test were defined simply as the critical displacement divided by the critical load.
The shorter fatigue delamination onset tests were performed on a servo-hydraulic MTS test system with a special fixture similar to that shown in Figure 3.3, which enables up to four 4ENF test samples to be cycled together with load monitoring on each station. The longer duration fatigue tests were performed on a multi-station test machine designed at MERL for high cycle testing. The tests on the servo-hydraulic equipment were run at 10Hz. The high cycle mode II tests were not run but were replaced by the additional tests.

3.3 Mixed Mode MMB tests

A list of all of the tests performed is given in Appendix 1.

The MMB specimen is similar to a DCB configuration consisting of a rectangular, uniform thickness, laminated composite with a non-adhesive insert on the mid-plane which serves as the

delamination initiator. The MMB test fixture (see Figure 3.6) enables both the Mode I (opening) and Mode II (bending) modes to be applied to the specimen in proportions dependant on the ratio of c and L.

The fixture used is that suggested by the draft ASTM MMB standard. Opening forces were applied using piano hinges bonded to the specimen and bending forces by a roller at distance L from the piano hinge.

The samples for the MMB tests were fabricated in S2/8552 and IM7/8552 and with a nominal width of 20 mm. The nominal thickness of the samples was 4.3 mm for the IM7/8552 samples and 5.6 mm for the S2/8552 samples. The initial delamination length (a_0) was nominally 25 mm.

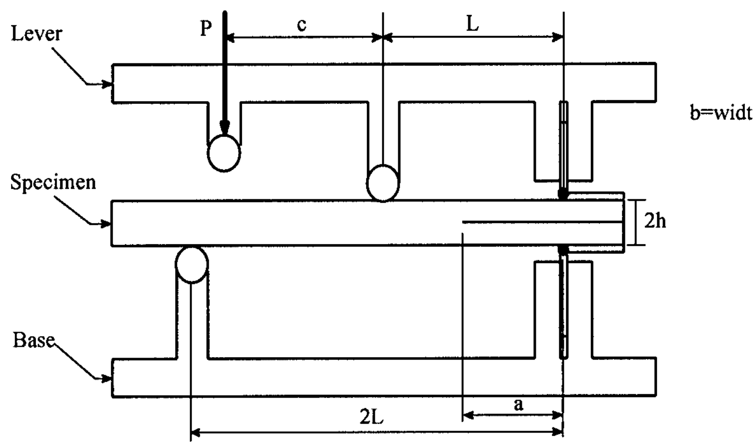


Figure 3.6 MMB test arrangement

A span length of 100mm (2L) was used to allow the end of the insert to be near the mid position in the fixture.

Material properties are required for the data reduction of the MMB. The material properties supplied by BHTI were:

E_{22}	12.27 GPa	G_{13}	4.83 GPa	for S2/8552 and
E_{22}	9.1 GPa	G_{13}	5.19 GPa	for IM7/8552

Tests were performed at mode ratios (m) of G_{II}/G_{tot} 0.66 and G_{II}/G_{tot} 0.33. The tests at G_{II}/G_{tot} 0.66 required a lever arm length set at 32mm and the tests at G_{II}/G_{tot} 0.33 required a lever arm length set at 57mm.

The quasi-static tests were all conducted on a screw driven Lloyd test machine at a constant rate of 0.5mm/min.

Three samples were tested for each material. The thickness and width of each test specimen was measured at three points along the length and the average value determined and used for the calculations of G. The edge of each test specimen was then coated in water-based typewriter correction fluid and a grid marked starting with the first line at a_0. Lines were then marked at 1mm intervals for the first 10mm and subsequently at 5mm intervals to a crack length of at least 50mm.

As the load increased the delamination length was measured on one side of the test specimen using a deep field microscope at approximately x25 magnification. At relevant intervals of delamination length the load and deflection were noted. Throughout the test, the load/deflection trace was stored in the computer and this was used to check the accuracy of the noted readings at the end of the test.

The shorter duration fatigue delamination onset tests were performed on a servo-hydraulic MTS test system with a special fixture similar to that in Figure 3.3 which enables up to four MMB test samples to be cycled together with load monitoring on each station. The longer duration fatigue tests were performed on a multi-station test machine designed at MERL for high cycle testing. The tests on the servo-hydraulic equipment were run at 10Hz. It was intended to run the long duration tests on the multi-station test machine at 20Hz. However, problems with the fixtures resulted in some of the locking nuts coming loose. Therefore, tests were run at lower frequencies.

Figure 3.7 shows an MMB test fixture on the multi-station test machine.

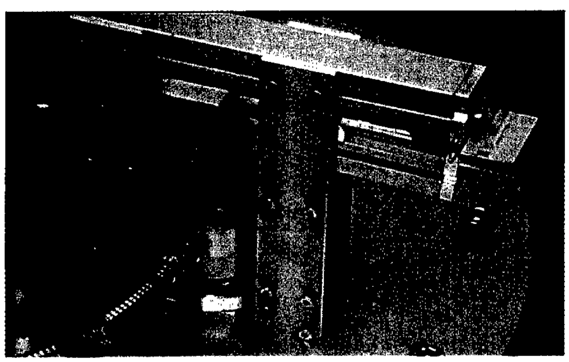


Figure 3.7 MMB test fixture on multi-station test machine

The tests were generally stopped when the initial sample compliance had changed by more than 5%, or after 100Mc, whichever was the sooner.

4.0 RESULTS AND DISCUSSION

4.1 Static tests

Plots of compliance vs. delamination length and G vs. delamination length (R-curves) are given for the DCB tests in Appendix 2 and for the 4ENF tests in Appendix 3. For the MMB tests R-curves are given for tests at G_{II}/G_{tot} 0.33 in Appendix 4 and for the tests at G_{II}/G_{tot} 0.66 in Appendix 5. The reduced data from all of the static tests for the DCB (Mode I), 4ENF (Mode II) and MMB (combination of Mode I and Mode II) are given in Table 1. The NL (data taken from deviation from linearity of the loading curve) data reduction method has been used for all types of test.

Table 4.1 Static test data for DCB, 4ENF and MMB tests for S2/8552 and IM7/8552

Test	G_{II}/G_{tot}	Test #	G_c^{NL} (J/m^2)	
			S2/8552 (sample #)	IM7/8552 (sample #)
DCB	0	1	266 (#10)	217 (#3)
		2	191 (#14)	200 (#14)
		3	306 (#5)	207 (#1)
		Mean sd	254 58	208 8.5
4ENF	1	1	1961 (#2)	1229 (#1)
		2	1679 (#13)	1108 (#3)
		3	1637 (#7)	1665 (#8)
		Mean sd	1759 176	1334 293
MMB	0.66	1	808 (#10)	349 (#6)
		2	679 (#7)	493 (#19)
		3	762 (#6)	280 (#26)
		Mean sd	750 65	374 109
MMB	0.33	1	403 (#3)	250 (#1)
		2	434 (#1)	322 (#10)
		3	412 (#19)	323 (#22)
		Mean sd	416 16	298 42

The mean Mode I static toughness is slightly higher for the S2/8552 than it is for the IM7/8552, although there is larger scatter in the data. In Mode II and Mixed Mode loading, the fracture toughness is also higher for the S2/8552 than for the IM7/8552. The mean fracture toughness for the IM7/8552 at a mode ratio of 0.66 is higher than the toughness at ratio of 0.33, although there is a large scatter in the 0.66 data resulting in an overlap of some of the data points. From the static DCB tests the values of m and D were also generated for use in the fatigue delamination onset tests. These data is given in Table 4.2.

Table 4.2 Values of m and Δ from static DCB tests

Sample	material	m	D
DCB #'5	S2/8552	5.72e-3	21.56
DCB #10	S2/8552	5.75e-3	18.46
DCB #14	S2/8552	5.83e-3	18.84
average		5.77e-3	19.62
DCB #1	IM7/8552	6.49e-3	5.25
DCB #3	IM7/8552	6.61e-3	5.09
DCB #14	IM7/8552	6.44e-3	5.52
average		6.51e-3	5.29

The mean values of interlaminar fracture toughness data are summarised in Figure 4.1 for the various Mode mixtures.

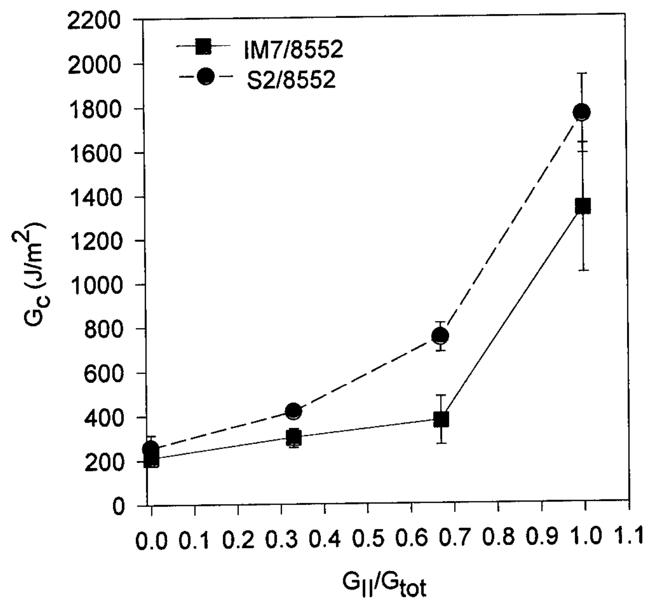


Figure 4.1 Mixed Mode Static Interlaminar Fracture Toughness

4.2 Mode I DCB delamination onset tests

A summary of the fatigue delamination onset tests is given in Appendix 6. The S2/8552 and IM7/8552data are plotted in Figure 4.2, with the static data plotted at 1 cycle.

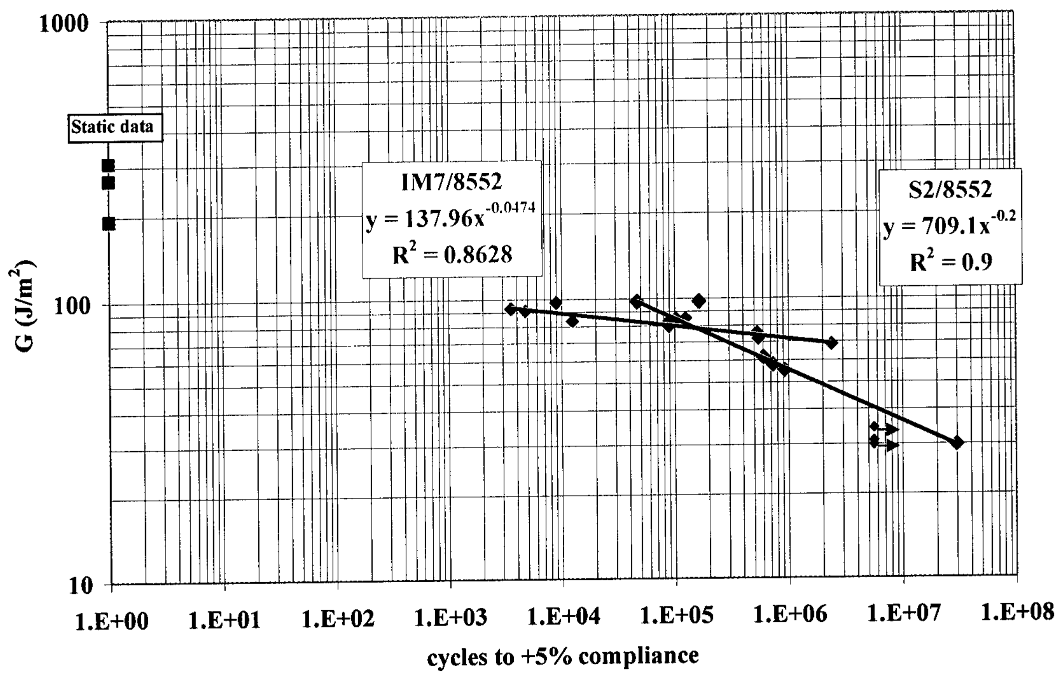


Figure 4.2 G-N curve for DCB tests on S2/8552 and IM7/8552

The IM7 specimens shown as run outs at approximately 6 million cycles showed no sign of increasing compliance. The specimens were therefore retested at higher G levels, when an electrical fault in the test machine caused the specimens fail prematurely.

4.3 Mode II 4ENF delamination onset tests

A summary of the fatigue delamination onset tests is given in Appendix 7. The S2/8552 data are plotted in Figure 4.3. Because of the additional DCB tests, not all of the 4ENF delamination onset tests were performed and the additional tests were held over to the current test programme. The curve fit line is therefore preliminary, as more data is required to give a better indication of the trends in the data.

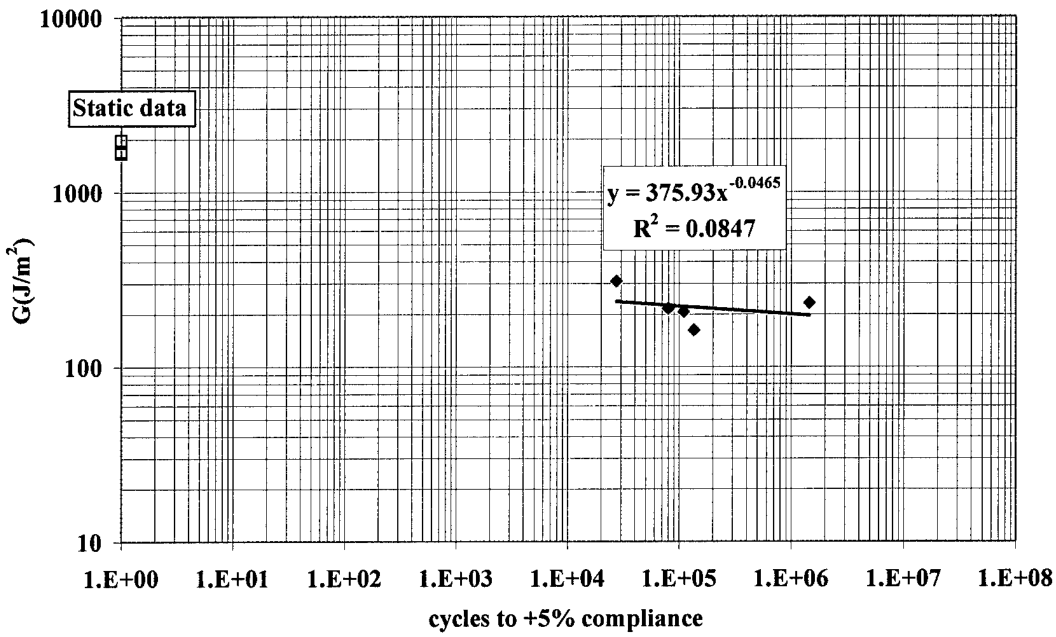


Figure 4.3 G-N curve for 4ENF tests on S2/8552

The data is plotted in Figure 4.4. As with the 4ENF tests on S2/8552, not all of the planned 4ENF tests were performed and the remaining tests will be performed in a future test programme. The curve fit line is therefore preliminary, as more data is required to give a better indication of the trends in the data.

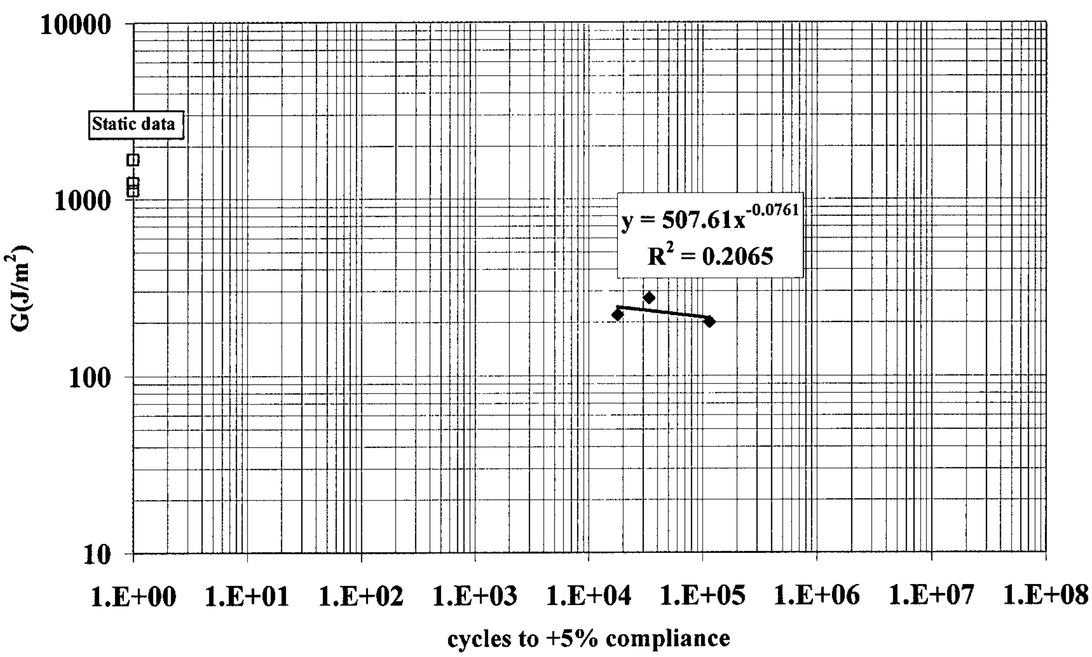


Figure 4.4 G-N curve for 4ENF tests on IM7/8552

4.4 Mixed Mode MMB delamination onset tests

A summary of the fatigue delamination onset tests is given in Appendix 8. The data is plotted in Figure 4.5.

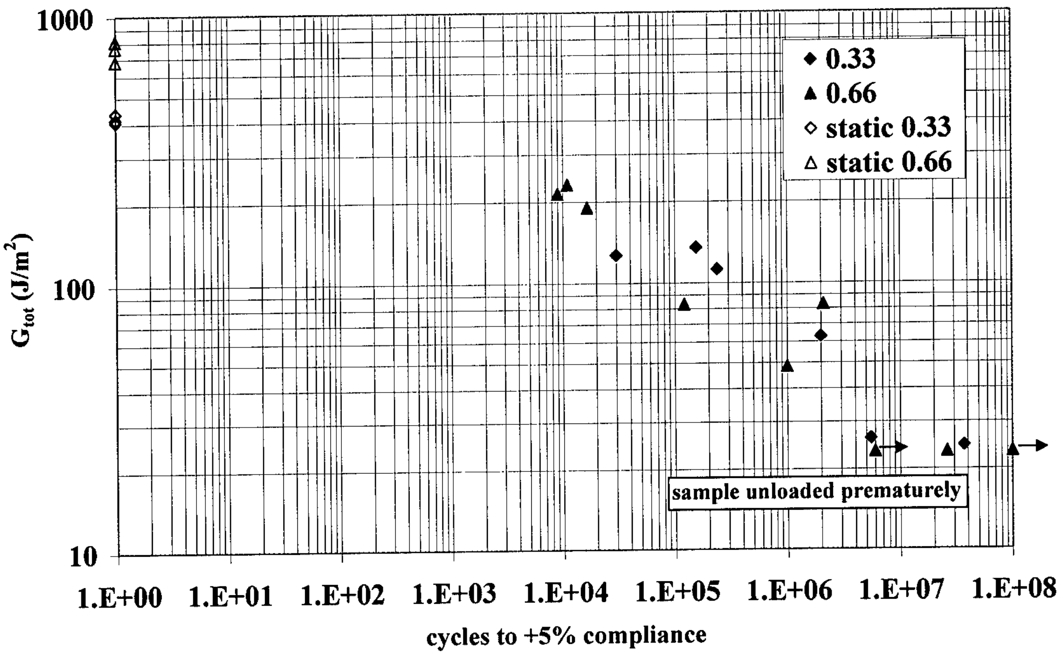


Figure 4.5 G-N curve for MMB tests on S2/8552

During the running of the MMB tests on the multi-station test equipment, some of the test fixtures vibrated loose so that the loads were not applied correctly to the specimens. In these cases the test was paused and the fixtures re-adjusted. The applied loads were also low. There is little difference in the delamination onset data at G_{II}/G_{tot} 0.33 and G_{II}/G_{tot} 0.66. This is contrary to the trend one may expect from the static data.

The IM7/8552 data are plotted in Figure 4.6.

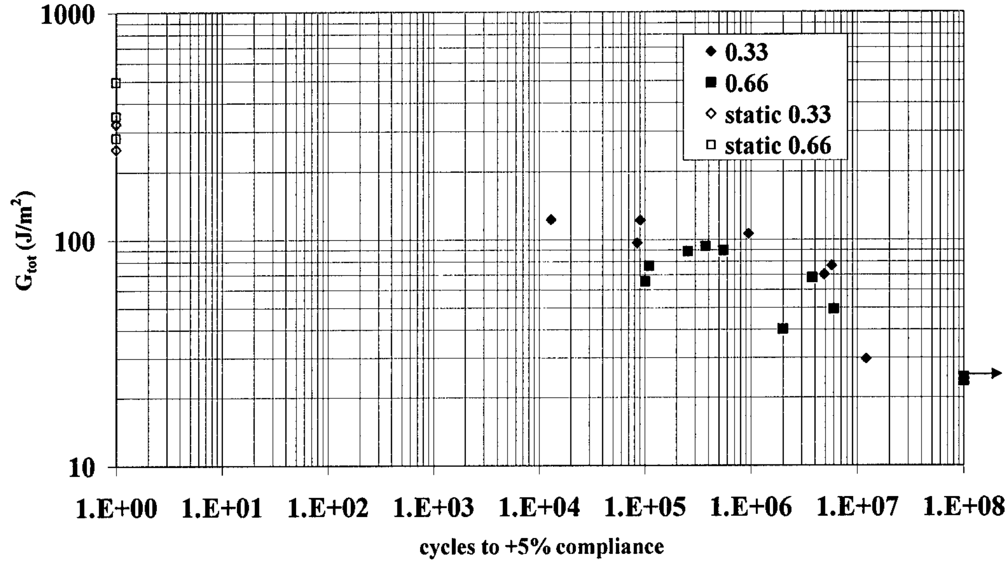


Figure 4.6 G-N curve for MMB tests on IM7/8552

There is again little difference in the delamination onset data at G_{II}/G_{tot} 0.33 and at G_{II}/G_{tot} 0.66. However, the static data at these mode ratios is relatively close together, and in some cases the static data overlaps.

The fracture toughness between G_{II}/G_{tot} 0 (Mode I) and G_{II}/G_{tot} 0.66 for IM7/8552 is relatively flat. From these data one may expect the fatigue delamination onset data between G_{II}/G_{tot} 0.33 to G_{II}/G_{tot} 0.66 to be similar.

A comparison of the Mode I, Mode II and mixed mode data for S2/8552 is given in Figure 4.7.

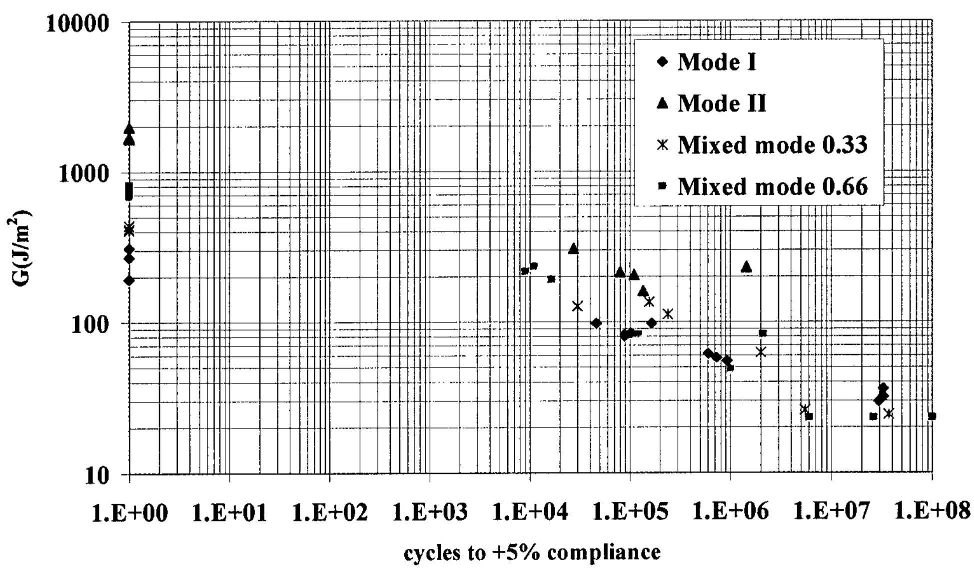


Figure 4.7 Summary of test data for S2/8552

The static data, in particular, follows the expected trend of an increase in toughness with an increase in Mode II. The difference between the fatigue data for the different mode ratios does not lead to such a clearly defined difference as seen in the static data with the Mode I and mixed mode data overlapping, especially at lower G levels. There is currently insufficient Mode II data at high cycle/low G levels to allow a definite conclusion to be reached, although the current data does indicate a higher G level for similar cycles to onset when compared with the Mode I data.

A comparison of the Mode I, Mode II and mixed mode data or IM7/8552 is given in Figure 4.8.

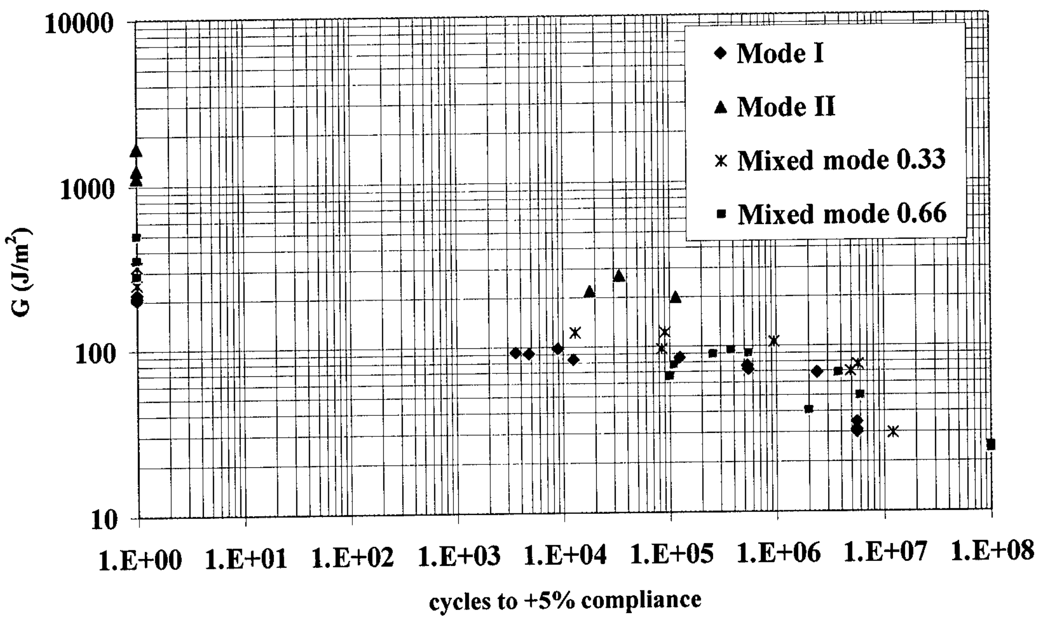


Figure 4.8 Summary of test data for IM7/8552

The static data, as with the data for S2/8552, follows the expected trend of an increase in toughness with an increase in Mode II. The mixed mode data at G_{II}/G_{tot} 0.33 and at G_{II}/G_{tot} 0.66 is, however, closer to the Mode I data than is seen with S2/8552. As seen in the S2/8552 data, there is some data overlap, especially at lower G levels, although the mixed mode data is generally at a higher G level for the same cycles to onset. There is also currently insufficient Mode II data at high cycle/low G levels to allow a definite conclusion to be reached, although the current data does indicate a higher G level for similar cycles to onset when compared with the Mode I and mixed mode data.

5.0 CONCLUSIONS

Use has been made of a unique multi-station test machine designed and developed at MERL for the delamination testing of composite materials alongside multi-station testing using servo-hydraulic test equipment.

The mean Mode I static toughness is 22% higher for the S2/8552 than it is for the IM7/8552, although there is larger scatter in the data.

In Mode II and Mixed Mode loading, the static fracture toughness is also higher for the S2/8552 than for the IM7/8552. The mean fracture toughness for the IM7/8552 at a mode ratio of 0.66 is higher than the toughness at ratio of 0.33, although there is a large scatter on the 0.66 data resulting in an overlap of some of the data points.

The static data follows the expected trend of an increase in toughness with an increase in Mode II for both S2/8552 and IM7/8552.

The difference between the fatigue data for the mixed mode ratios for S2/8552 is not clearly defined, as seen in the static data. The Mode I and mixed mode data overlaps, especially at lower G levels. There is little difference in the delamination onset data at G_{II}/G_{tot} 0.33 and G_{II}/G_{tot} 0.66.

The IM7/8552 mixed mode data at G_{II}/G_{tot} 0.33 and at G_{II}/G_{tot} 0.66 is closer to the Mode I data than with S2/8552. In the S2/8552 data, there is some data overlap, especially at lower G levels, although the mixed mode data is generally at a higher G level for the same cycles to onset.

Difficulties were encountered with the vibration of fixtures on the multi-station high-cycle fatigue test machine. This vibration occasionally caused the test fixtures to come loose and the load applied load to reduce. Therefore some test specimens were not tested to the load/displacement levels expected. In these cases the test was paused and the fixtures adjusted to ensure the load is applied as expected. The test was then restarted.

Appendix 1

Summary of all test samples and the tests performed

S2/8552 DCB tests RT dry

sample #	max disp (mm)	Freq (Hz)
5	-	static
10	-	static
14	-	static
3	2	5
7	2	5
12	2	5
4	1.88	5
8	1.88	5
1	1.75	5
9	1.75	5
11	1.75	5
2	1	5
6	1	5
13	1	5

IM7/8552 DCB tests RT dry

sample #	max disp (mm)	Freq (Hz)
1	-	static
3	-	static
14	-	static
4	1.5	5
7	1.5	5
13	1.5	5
6	1.35	5
8	1.35	5
5	1.2	5
10	1.2	5
12	1.2	5
2	0.85	5
9	0.85	5
11	0.85	5

IM7/8552 4ENF tests

sample #	max disp (mm)	Freq (Hz)
1	-	static
3	-	static
8	-	static
4	1	5
14	0.8	5
11	0.6	5
2	untested	-
5	untested	-
6	untested	-
7	untested	-
9	untested	-
10	untested	-
12	untested	-
13	untested	-

S2/8552 4ENF tests

sample #	max disp (mm)	Freq (Hz)
2	-	static
7	-	static
13	-	static
4	1	5
6	0.81	5
10	0.81	5
1	0.81	5
12	0.8	5
3	untested	-
5	untested	-
8	untested	-
9	untested	-
11	untested	-
14	untested	-

IM7/8552 MMB tests

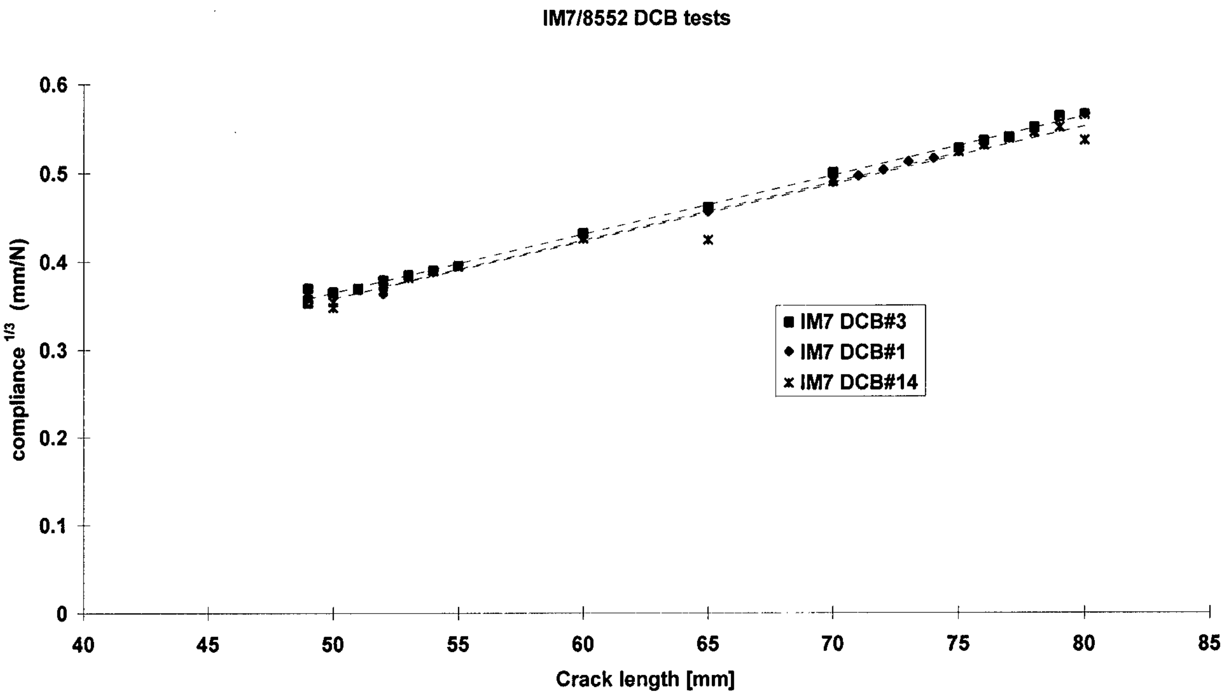
sample #	GII/G nom %	max disp (mm)	Freq (Hz)
1	33	-	static
6	66	-	static
10	33	-	static
19	66	-	static
22	33	-	static
26	66	-	static
2	33	0.76	5
12	33	0.76	5
27	33	0.76	5
18	66	0.76	10
21	33	0.76	10
7	66	0.75	5
11	66	0.75	5
23	66	0.75	5
4	66	0.71	10
16	33	0.71	10
5	66	0.65	20
8	33	0.65	20
13	33	0.65	20
14	33	0.65	20
17	33	0.65	20
20	66	0.65	20
25	33	0.65	20
9	66	0.45	20
15	66	0.45	20
24	66	0.45	20
28	0.66	untested	-

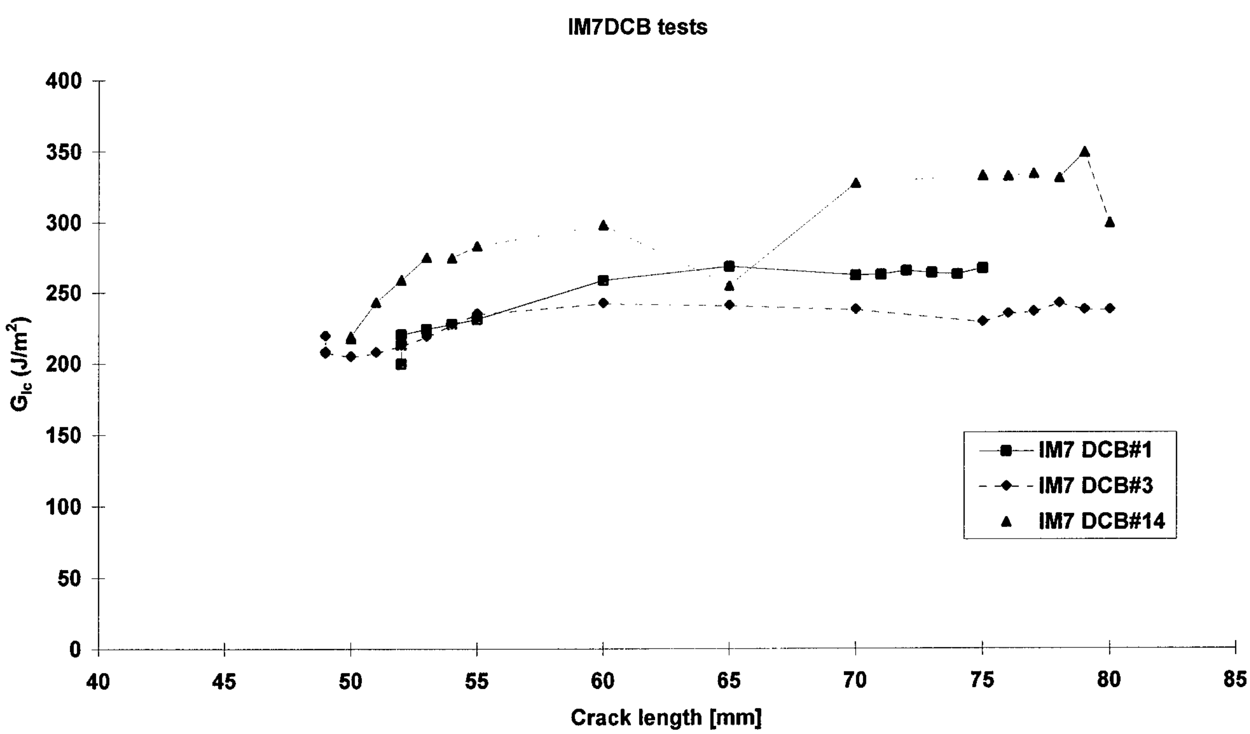
S2/8552 MMB tests

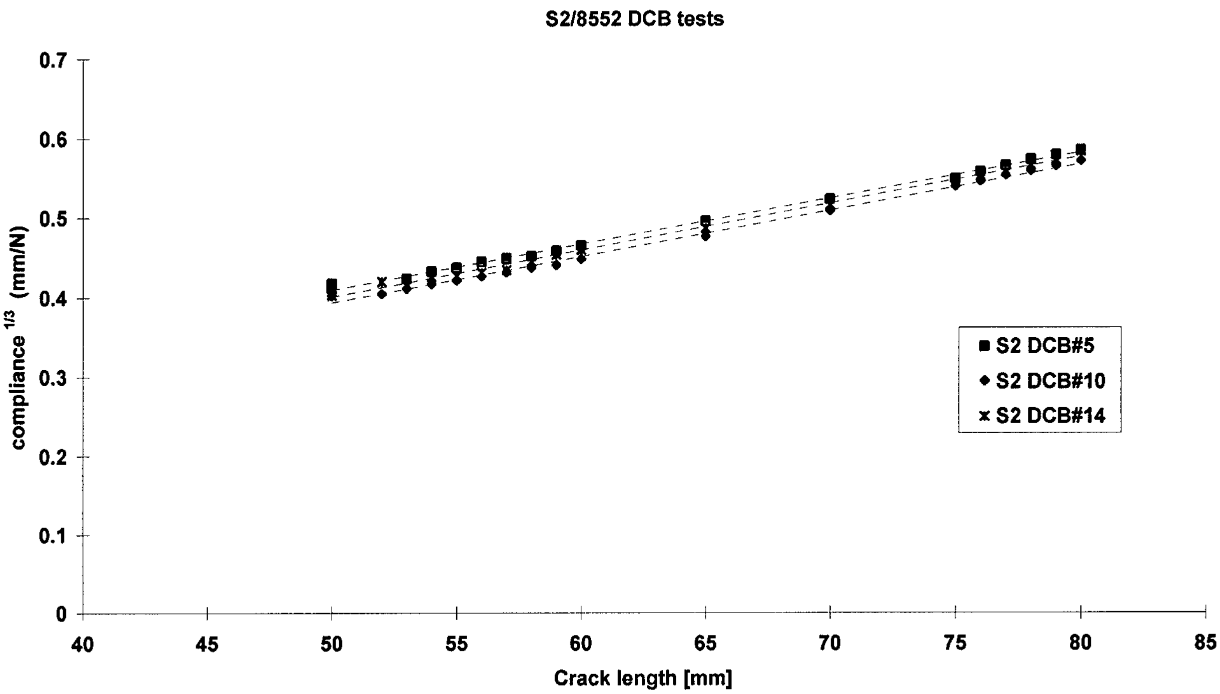
sample #	GII/G nom %	max disp (mm)	Freq (Hz)
3	33	-	static
6	66	-	static
7	66	-	static
10	66	-	static
14	33	-	static
19	33	-	static
8	66	1.30	5
11	66	1.30	5
28	66	1.30	5
12	33	0.80	20
21	33	0.80	20
23	33	0.80	20
1	33	0.65	20
2	33	0.65	20
4	66	0.65	20
9	33	0.65	20
16	66	0.65	20
17	66	0.65	20
25	33	0.65	20
26	33	0.65	20
27	66	0.65	20
5	66	0.45	20
20	66	0.45	20
24	66	0.45	20
13	untested	-	-
15	untested	-	-
18	untested	-	-
22	untested	-	-

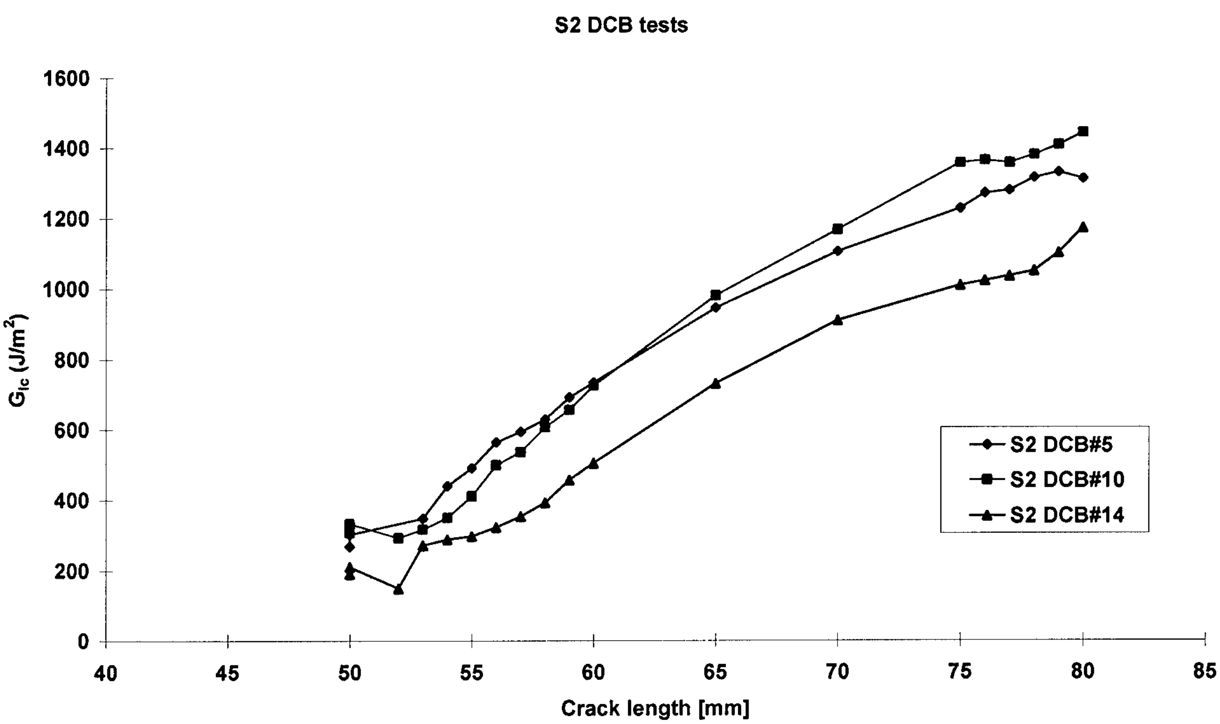
Appendix 2

Static data from DCB tests


IM7/8552 DCB tests
compliance $^{1/3}$ (mm/N)
Crack length [mm]
IM7 DCB#3
IM7 DCB#1
IM7 DCB#14
0.6
0.5
0.4
0.3
0.2
0.1
0
40
45
50
55
60
65
70
75
80
85

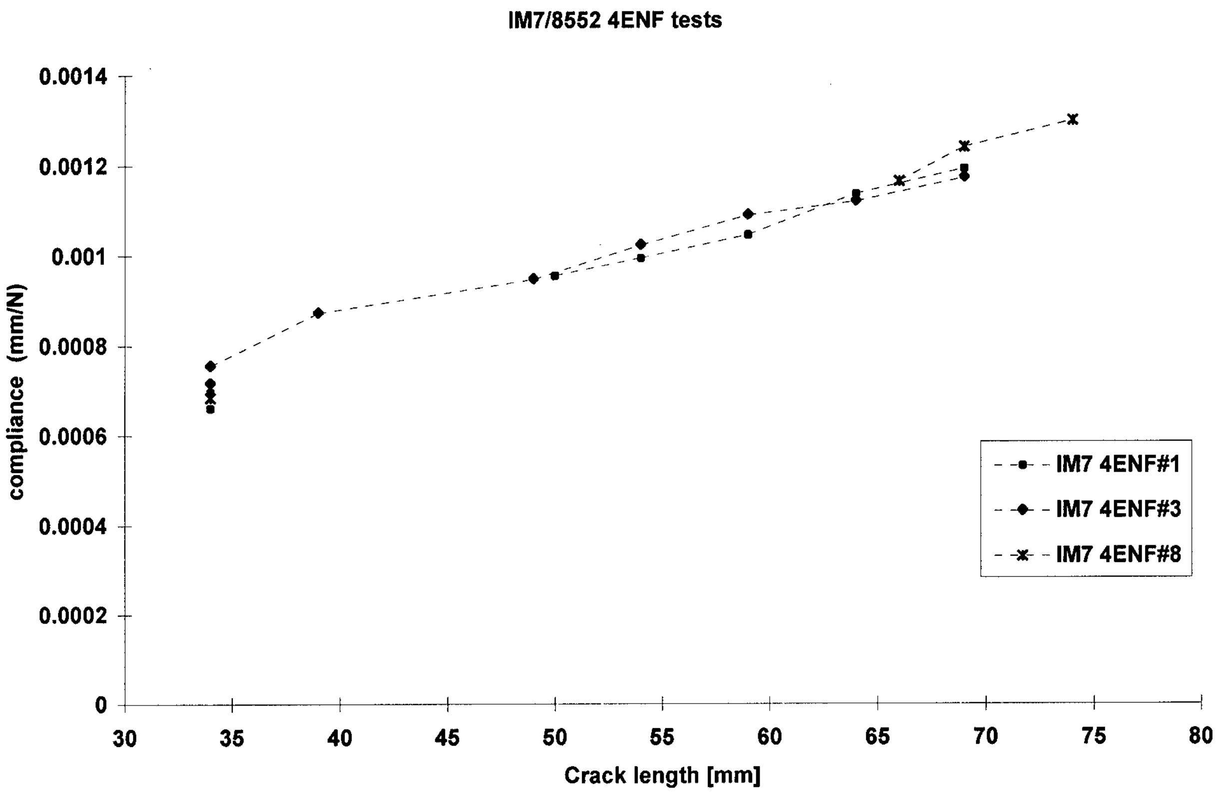

IM7DCB tests
G_{Ic} (J/m^2)
Crack length [mm]
IM7 DCB#1
IM7 DCB#3
IM7 DCB#14
400
350
300
250
200
150
100
50
0
40
45
50
55
60
65
70
75
80
85

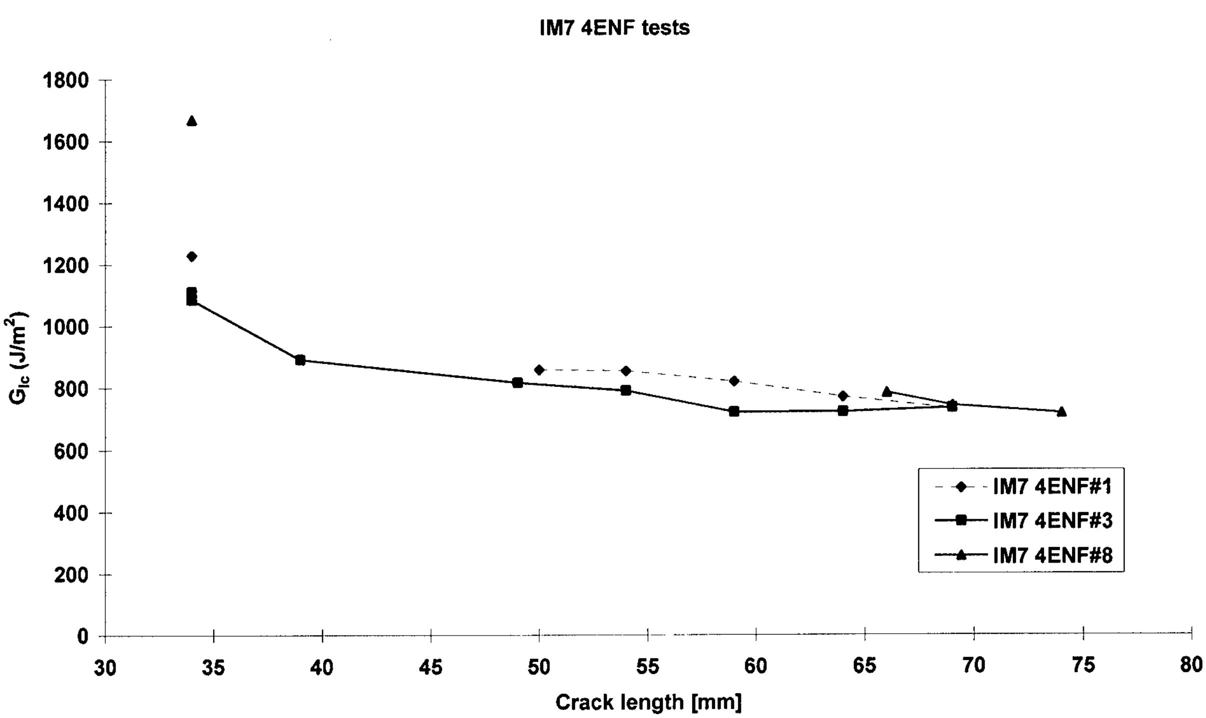

S2/8552 DCB tests
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
compliance 1/3 (mm/N)
40
45
50
55
60
65
70
75
80
85
Crack length [mm]
S2 DCB#5
S2 DCB#10
S2 DCB#14

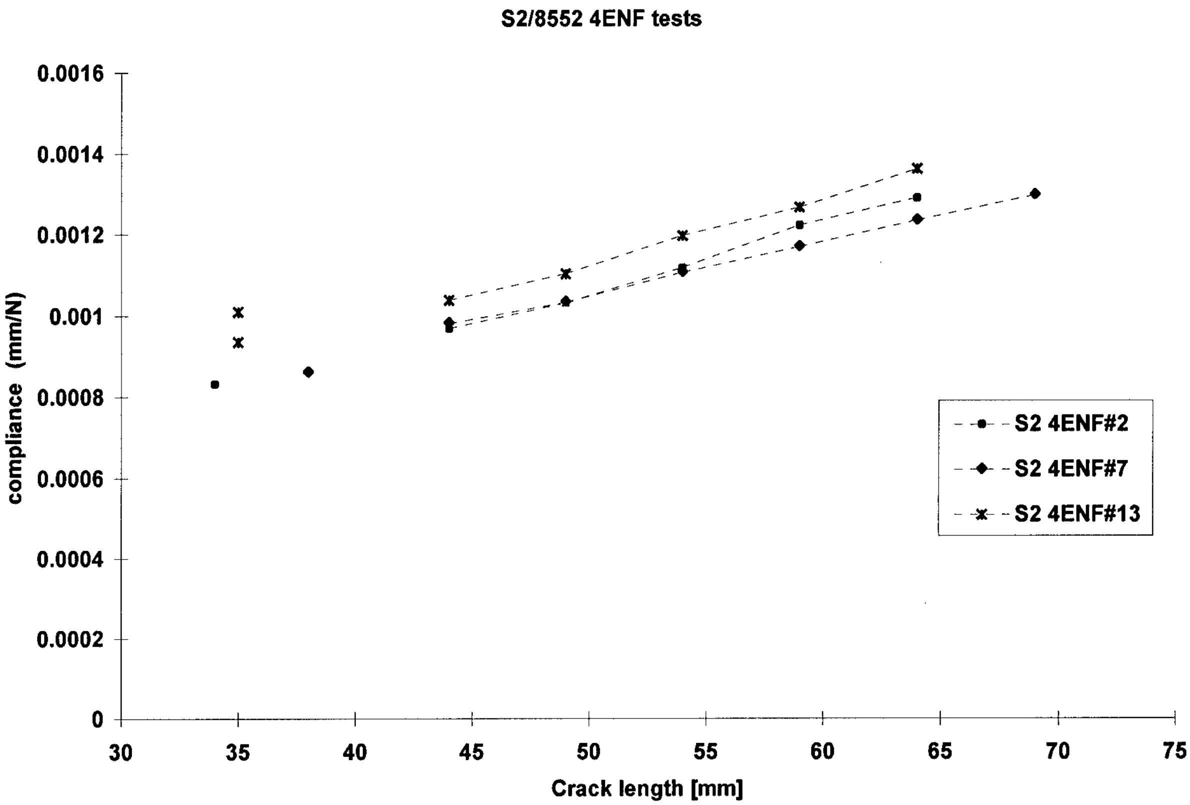

S2 DCB tests
1600
1400
1200
1000
800
600
400
200
0
Gₗc (J/m²)
40
45
50
55
60
65
70
75
80
85
Crack length [mm]
S2 DCB#5
S2 DCB#10
S2 DCB#14

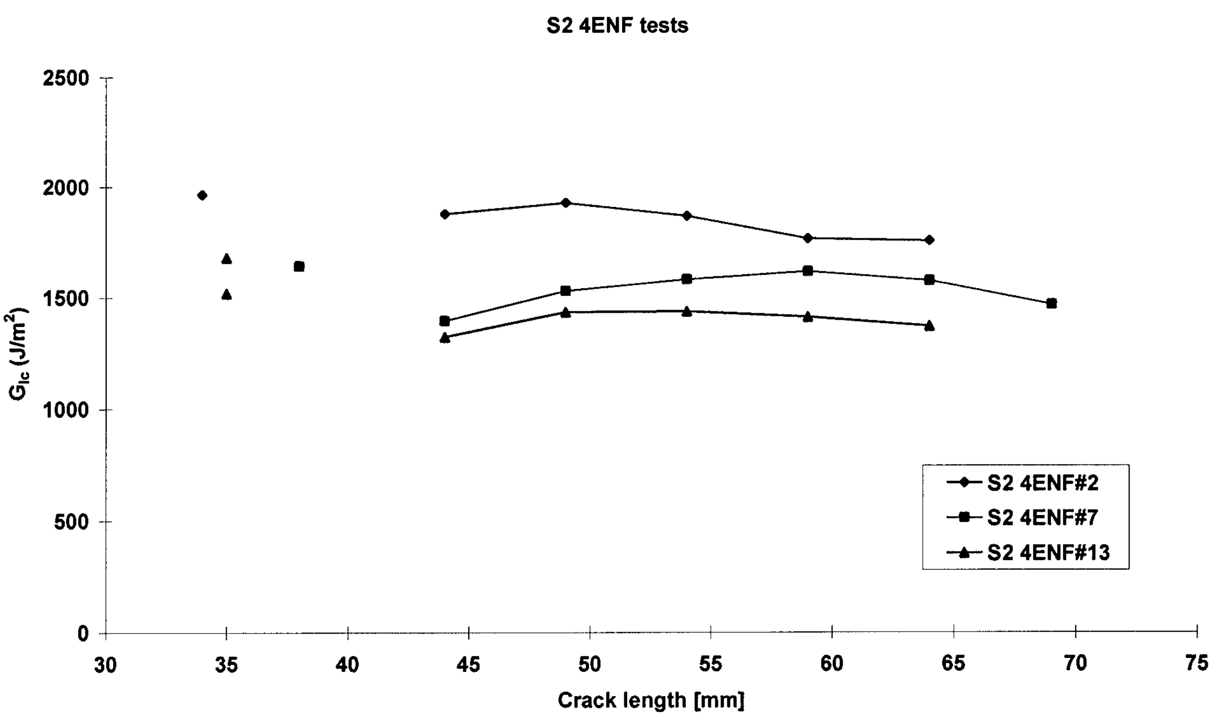
Appendix 3

Static data from 4ENF tests


IM7/8552 4ENF tests
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
compliance (mm/N)
30
35
40
45
50
55
60
65
70
75
80
Crack length [mm]
IM7 4ENF#1
IM7 4ENF#3
IM7 4ENF#8

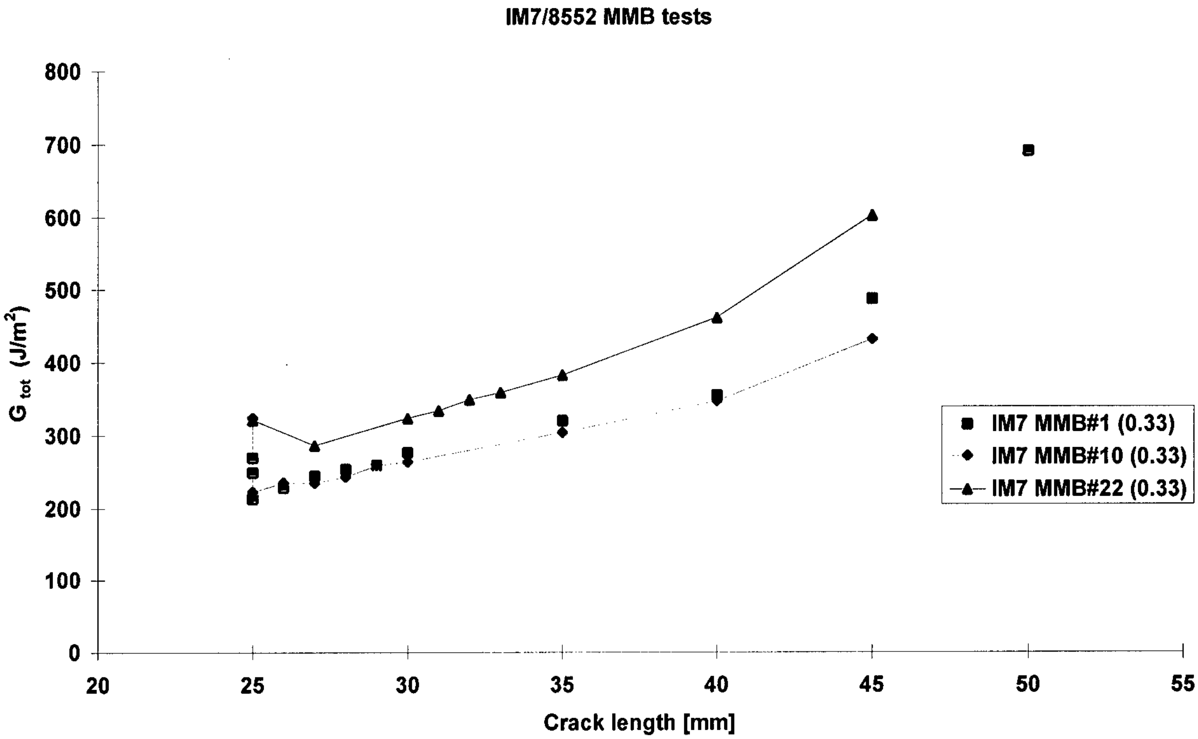

IM7 4ENF tests
1800
1600
1400
1200
1000
800
600
400
200
0
G_{Ic} (J/m^2)
30
35
40
45
50
55
60
65
70
75
80
Crack length [mm]
IM7 4ENF#1
IM7 4ENF#3
IM7 4ENF#8

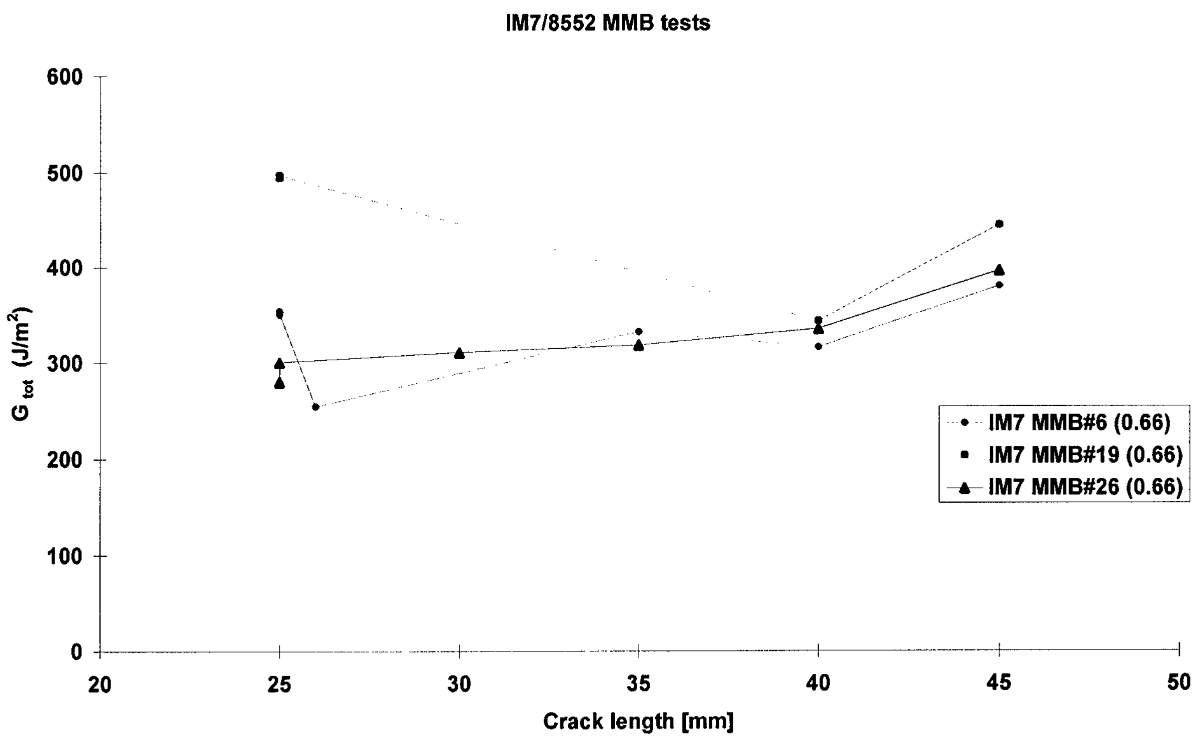

S2/8552 4ENF tests
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
compliance (mm/N)
30
35
40
45
50
55
60
65
70
75
Crack length [mm]
S2 4ENF#2
S2 4ENF#7
S2 4ENF#13


S2 4ENF tests
2500
2000
1500
1000
500
0
G_{Ic} (J/m^2)
30
35
40
45
50
55
60
65
70
75
Crack length [mm]
S2 4ENF#2
S2 4ENF#7
S2 4ENF#13

Appendix 4

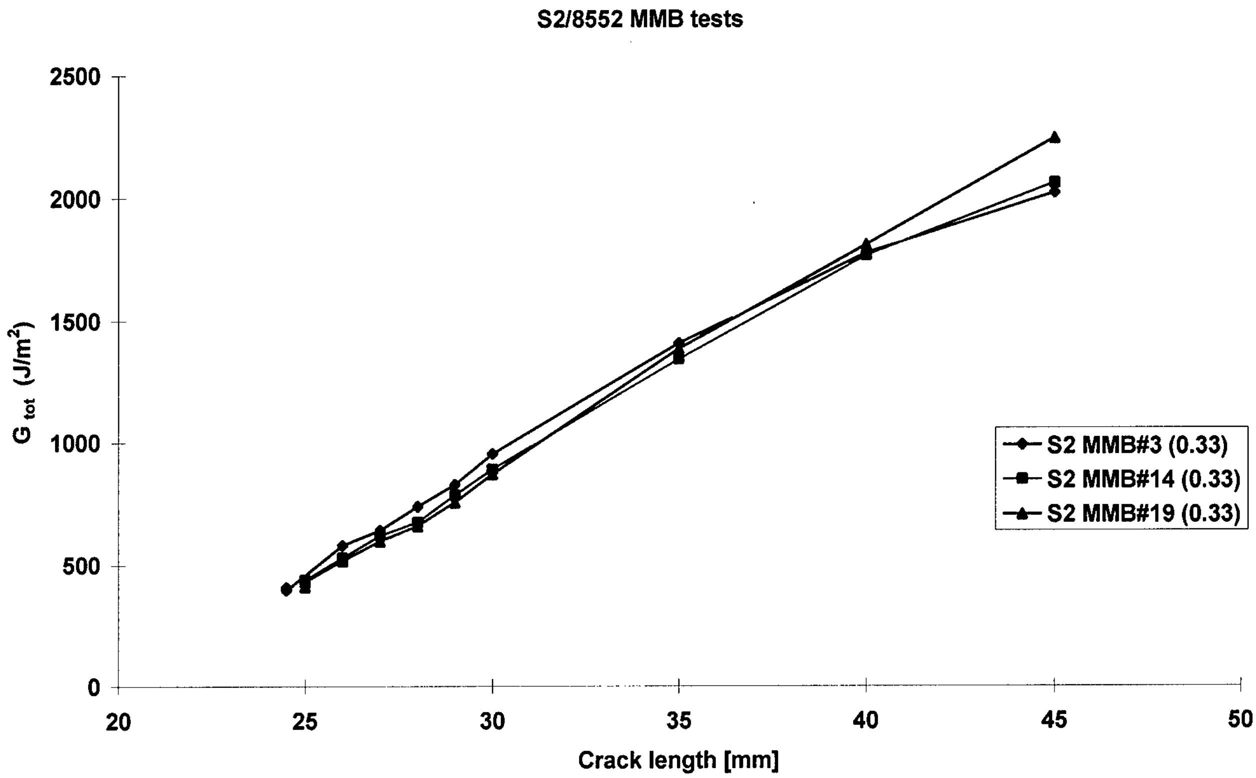
Static data from MMB tests at G_{II}/G_{tot}=0.33

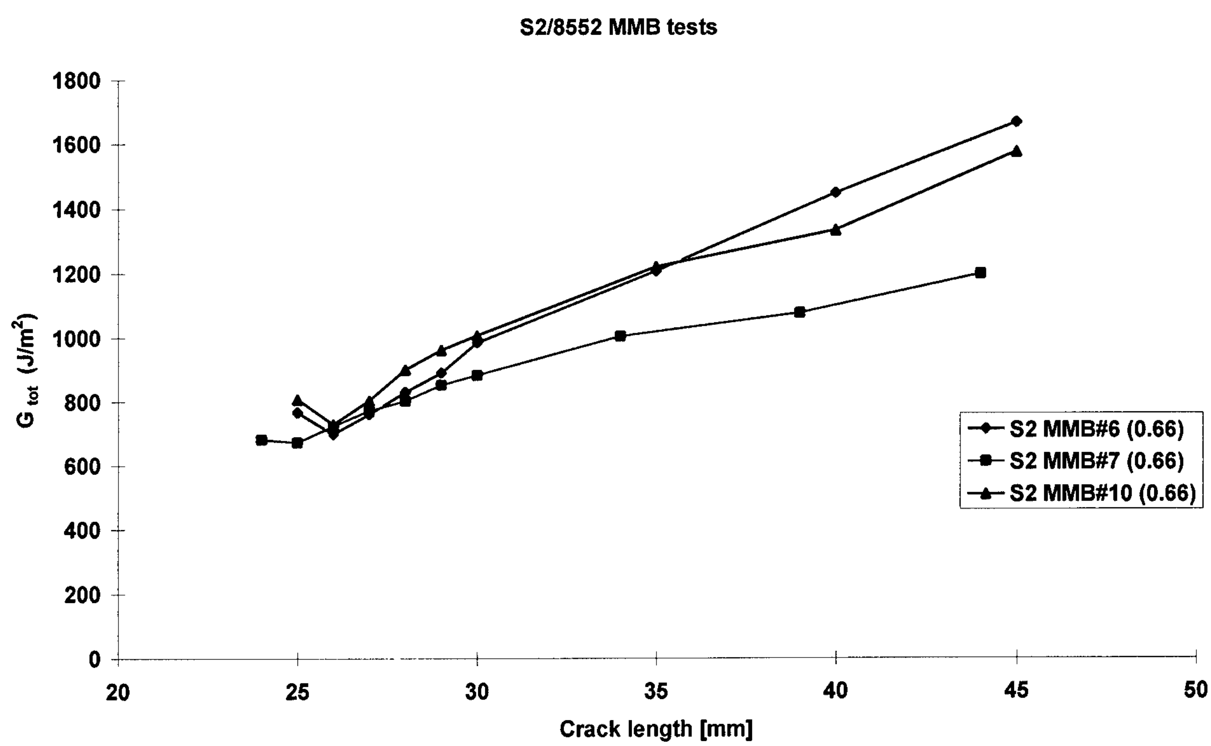

IM7/8552 MMB tests
800
700
600
500
400
300
200
100
0
G tot (J/m2)
20
25
30
35
40
45
50
55
Crack length [mm]
IM7 MMB#1 (0.33)
IM7 MMB#10 (0.33)
IM7 MMB#22 (0.33)


IM7/8552 MMB tests
600
500
400
300
200
100
0
G tot (J/m2)
20
25
30
35
40
45
50
Crack length [mm]
IM7 MMB#6 (0.66)
IM7 MMB#19 (0.66)
IM7 MMB#26 (0.66)

Appendix 5

Static data from MMB tests at $G_{II}/G_{tot}=0.66$


S2/8552 MMB tests
2500
2000
1500
1000
500
0
G tot (J/m²)
20
25
30
35
40
45
50
Crack length [mm]
S2 MMB#3 (0.33)
S2 MMB#14 (0.33)
S2 MMB#19 (0.33)


S2/8552 MMB tests
1800
1600
1400
1200
1000
800
600
400
200
0
G tot (J/m²)
20
25
30
35
40
45
50
Crack length [mm]
S2 MMB#6 (0.66)
S2 MMB#7 (0.66)
S2 MMB#10 (0.66)

Appendix 6

Summary of DCB tests performed

S2/8552 DCB tests RT dry

sample	dmax (mm)	comp initial (mm/N)	Pmax (N)	a0 (mm)	b (mm)	N5% (cycles)	Gimax (J/m^2)	comments
2	1	0.067	30	50	20.4	32797000	31.7	to be continued
6	1	0.067	34	50	20.41	32797000	35.9	to be continued
13	1	0.075	28	50	20.4	29706000	29.6	
1	1.75	0.057	33	50	20.37	604600	61.1	
9	1.75	0.062	30	51	20.33	928000	54.9	
11	1.75	0.061	31	50	20.34	730850	57.5	
4	1.88	0.0606	48	50	20.1	165000	96.7	
8	1.88	0.0603	48	50	20.1	46500	96.7	
3	2	0.061	39	51	20.27	89000	81.7	
7	2	0.061	40	51	20.29	103000	83.7	
12	2	0.06	38	51	20.3	89000	79.5	

Statics

sample	cycles	Gimax (J/m^2)
5	1	266.1
10	1	306.1
14	1	190.8

IM7/8552 DCB tests RT dry

sample	dmax (mm)	Pmax (N)	a0 (mm)	b (mm)	N5% (cycles)	Gimax (J/m^2)	Comments
2	0.85	30	50	20.32	5600000	34.0	samples retested at higher G
9	0.85	26	50	20.27	5600000	29.6	samples retested at higher G
11	0.85	27	50	20.29	5600000	30.7	samples retested at higher G
5	1.2	42	50	20.14	3400000	67.9	pump cut out and damaged samples
10	1.2	44	50	20.18	3400000	71.0	pump cut out and damaged samples
12	1.3	40	50	20.29	3400000	69.5	pump cut out and damaged samples
6	1.35	55	50	20.1	4770	100.2	
8	1.35	56	50	20.1	3575	102.0	
4	1.5	42	50	20.26	124950	84.4	
7	1.5	41	50	20.1	12500	83.0	
13	1.5	48	50	20.23	8940	96.6	
2	1.3	41	50	20.32	545000	71.2	
9	1.3	43	50	20.27	533065	74.8	
11	1.2	42	50	20.15	2390000	67.9	

Statics

sample	cycles	Gimax (J/m^2)
1	1	199.7
3	1	206.5
14	1	216.9

Appendix 7

Summary of 4ENF tests performed

S2/8552 4ENF tests

Fatigue tests

sample	dmax (mm)	comp initial (mm/N)	Pmax (N)	b (mm)	N5% (cycles)	Gimax (J/m^2)
1	0.81	0.001	740	20.41	110,000	203.6
6	0.81	0.001	755	20.37	80,000	212.3
10	0.81	0.00114	655	20.4	136,000	159.6
4	1	0.00102	905	20.4	27400	304.7
12	0.8	0.00104	784	20.4	1450000	228.6

Statics

sample	N5% (cycles)	Gmax (J/m^2)
2	1	1961.2
7	1	1637.4
13	1	1679.1

IM7/8552 4ENF tests

Fatigue tests

sample	dmax (mm)	comp initial (mm/N)	Pmax (N)	b (mm)	N5% (cycles)	Gmax (J/m^2)
11	0.6	0.00078	770	20.2	115,000	198.1
14	0.8	0.00088	808	20.31	18,000	216.9
4	1	0.00102	900	20.3	34,000	269.3

Statics

sample	N5% (cycles)	Gmax (J/m^2)
1	1	1228.8
3	1	1108.8
8	1	1665.9

Appendix 8

Summary of MMB tests performed

S2/8552 MMB tests

Specimen #	GII/G nom	dMax	b	2h	1/CO	ao	Delta a	a	Pmax	G(Ic)	G(IIc)	G(t)	%G(II)	N	Comments
	%	(max,nl,vis,a#)	mm	mm	N/m	mm	mm	mm	N	N/m	N/m	N/m	%		
21	33	0.8	20.26	5.66	98039	25	0	25	108	89.21	45.33	134.54	33.69	156000	
12	33	0.8	20.36	5.66	90909	25	0	25	101	83.48	42.62	126.10	33.80	30000	
23	33	0.8	20.36	5.65	91324	24	0	24	97	73.92	37.62	111.54	33.73	240000	
2	33	0.85	20.3	5.5	91324	25	0	25	71	41.29	21.05	62.33	33.77	2000000	
25	33	0.65	20.3	5.5	90910	25	0	25	60	29.61	15.10	44.72	33.77		fixtures vibrated loose
26	33	0.65	20.3	5.5	56000	25	0	25	36	16.99	8.89	25.88	34.35	5500000	
1	33	0.65	20.3	5.5	72000	25	0	25	47	22.75	11.75	34.50	34.07		fixtures vibrated loose
9	33	0.65	20.3	5.5	50000	25	0	25	33	15.91	8.37	24.28	34.47	37000000	

Static data

Sample	cycles	Gt
		N/m
3	1	403.3
14	1	434.1
19	1	412.3

Specimen	II/G no	dMax	b	2h	1/C0	ao	Delta a	a	Pmax	G(Ic)	G(IIc)	G(t)	%G(II)	N	Comments
	%	(max,nl,vis,a#)	mm	mm	N/m	mm	mm	mm	N	N/m	N/m	N/m	%		
8	66	1.30	20.24	5.55	190114	24	0	24	256	62.13	126.78	188.92	67.11	16500	
11	66	1.30	20.33	5.55	204082	24	0	24	284	70.19	142.46	212.65	66.99	9000	
28	66	1.30	20.29	5.51	181818	26	0	26	262	75.11	154.97	230.08	67.35	11000	
24	66	0.65	20.30	5.50	200000	25	0	25	130	15.85	32.34	48.19	67.11		fixtures vibrated loose
27	66	0.65	20.30	5.50	200000	25	0	25	130	15.85	32.34	48.19	67.11	1000000	
17	66	0.85	20.30	5.50	200000	25	0	25	170	27.10	55.31	82.41	67.11	121550	
16	66	0.85	20.30	5.50	200000	25	0	25	170	27.10	55.31	82.41	67.11	2100000	
20	66	0.45	20.26	5.74	200000	25	0	25	90	7.59	15.51	23.10	67.15	26100000	
5	66	0.45	20.27	5.63	200000	25	0	25	90	7.59	15.51	23.11	67.13	100000000	run out
24	66	0.45	20.28	5.69	200000	25	0	25	90	7.58	15.50	23.08	67.14	6000000	no load after 6Mc

Static data

Sample	cycles	Gt
		N/m
6	1	762.4
7	1	678.8
10	1	807.9

IM7/8552 MMB tests

Specimen #	GII/G nom	dMax	b	2h	1/C0	ao	Delta a	a	Pmax	G(Ic)	G(IIc)	G(t)	%G(II)	N	Comments
	%	(max,nl,vis,a#)	mm	mm	N/m	mm	mm	mm	N	N/m	N/m	N/m	%		
27	33	0.76	20.34	4.35	117647	25	0	25	104	70.3	35.0	105.3	33.2	950000	
12	33	0.76	20.25	4.36	125000	25	0	25	115	81.5	40.3	121.8	33.1	13000	
2	33	0.76	20.29	4.29	145000	25	0	25	110	64.5	31.5	96.0	32.8	85000	
14	33	0.65	20.30	4.30	65000	25	0	25	41	19.4	10.0	29.3	34.0	12100000	
25	33	0.65	20.30	4.30	80000	25	0	25	50	23.6	12.0	35.7	33.8		fixtures vibrated loose
8	33	0.65	20.30	4.30	260000	25	0	25	171	87.0	40.3	127.3	31.6		fixtures vibrated loose
17	33	0.65	20.31	4.38	142850	25	0	25	93	46.6	22.9	69.5	32.9	4895000	
16	33	0.71	20.30	4.30	63000	25	0	25	65	50.1	25.9	76.0	34.1	5750000	
21	33	0.76	20.30	4.30	115000	25	0	25	110	80.7	40.2	120.9	33.2	90850	

Static data

Sample	cycles	Gt
		N/m static 0.33
1	1	249.5
10	1	322.9
22	1	321.7

Specimen	II/G no	dMax	b	2h	1/C0	ao	Delta a	a	Pmax	G(Ic)	G(IIc)	G(t)	%G(II)	N	Comments
	%	(max,nl,vis,a#)	mm	mm	N/m	mm	mm	mm	N	N/m	N/m	N/m	%		
7	66	0.75	20.26	4.30	250000	25	0	25	201	29.8	59.0	88.79	66.43	550000	
11	66	0.75	20.22	4.32	264000	25	0	25	207	29.6	58.3	87.98	66.31	255000	
23	66	0.75	20.23	4.31	227272	25	0	25	175	25.3	50.6	75.94	66.64	110000	
20	66	0.65	20.22	4.30	160000	25	0	25	103	13.0	26.8	39.83	67.27	2000000	
5	66	0.65	20.23	4.30	200000	25	0	25	130	16.2	32.7	48.93	66.89	6000000	
13	66	0.65	20.30	4.30	250000	25	0	25	172	21.8	43.1	64.88	66.44	101000	
9	66	0.45	20.19	4.43	200000	25	0	25	90	7.8	15.7	23.46	66.92	100000000	run out
15	66	0.45	20.22	4.43	200000	25	0	25	90	7.7	15.7	23.43	66.92	100000000	run out
24	66	0.45	20.22	4.4	215000	25	0	25	96	8.1	16.3	24.44	66.77	100000000	run out
4	66	0.71	20.22	4.4	250000	25	0	25	175	22.6	44.8	67.35	66.46	3765000	
18	66	0.76	20.22	4.4	256000	25	0	25	208	31.0	61.3	92.31	66.40	376180	

Static data

Sample	cycles	Gt
		N/m
6	1	349.3
19	1	493.3
26	1	280.1